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IV. THE MECHANISM OF COUNTERCURRENTS OF DIFFERENT TEMPERATURES IN CYCLONES AND ANTICYCLONES.[1]

By Prof. FRANK H. BIGELOW, dated March 27, 1903.

THE WEATHER BUREAU CLOUD OBSERVATIONS.

The report on the international cloud observations of May 1, 1896, to July 1, 1897, Report of the Chief of the Weather Bureau, 1898–99, Vol. II, contained an outline description of a theory of the structure of cyclones and anticyclones, which was thought to be indicated as the probable interpretation of the motions of the air in cyclones and anticyclones. It was evident that a more complete insight into the mechanism of this type of motion in a fluid under atmospheric conditions would be afforded by the construction of systems of isobars on at least three planes having different elevations. For this purpose the sea level, the 3500-foot level, and the 10,000-foot level were selected, and suitable reduction tables have been made as described in the report on the barometry of the United States, Canada, and the West Indies, Report of the Chief of the Weather Bureau, 1900–1901, Vol. II. Since December 1, 1902, we have received daily reduced pressures on these planes from the regular stations of the United States and Canada, and the corresponding charts have been drawn with care by Mr. George Hunt of the Forecast Division. A definitive treatment of the problem evidently requires charts of the isotherms on the same planes, but it will not be necessary to wait for the completion of our discussion of the temperatures, because we have already obtained the approximate gradients needed in a preliminary study of this question. It is proposed to summarize the present status of the research, previous to working out an analytic treatment of the mechanism of tornadoes, cyclones, hurricanes, and the general circulation, from the data now in possession of the Weather Bureau.

THE GENERAL CIRCULATION.

The circulation of the atmosphere has been analyzed by meteorologists into (1) the general cold center cyclone, which covers a hemisphere of the earth from the pole to the equator, and (2) the local warm center cyclones and the anticyclones,

[1] No. I was published in the Monthly Weather Review for December, 1902, and Nos. II and III in that for January, 1903.

which drift eastward in the temperate latitudes. Ferrel worked out his well-known canal theory for the general cyclone, with northward motions in the upper and southward motions in the lower strata of the atmosphere. This theory was adopted by Oberbeck and carried out with difference of details, and it has been the prevailing view till the discussion of the Weather Bureau observations of 1896–97 in the United States proved that it is incorrect and must be greatly modified. No northward movement of importance exists in the upper strata, and there is no calm belt separating the eastward drift from a westward current in the polar zone. In the Tropics the motions are substantially those deduced by Ferrel, and they result naturally from the equations of motion on a rotating earth heated in the equatorial belt. Professor Hildebrandsson's report on the International Cloud Observations confirms these facts for Europe and Asia generally, and therefore we conclude that they are fundamental, and that the canal theory must be finally abandoned. The Weather Bureau report showed that the incoming solar radiation of short waves heats the atmosphere only a little, but that it does heat up the earth's surface. This latter radiates much longer heat waves at terrestrial temperatures, and thereby the lower strata of the atmosphere are heated up by convection currents to a distance of two or three miles. This heat energy is very vigorous in the Tropics, and produces currents of warm air which leak outward and flow toward the poles only in the lower strata instead of in the high levels, determining by their motion the local distributions of pressure near the surface of the earth. By an analogous process cold currents flow from the higher latitudes toward the equator at low or moderate elevations. These counter currents meet in the middle latitudes, as over the United States, and we have now to study the action of the resulting mechanism.

THE LOCAL CIRCULATION IN CYCLONES AND ANTICYCLONES.

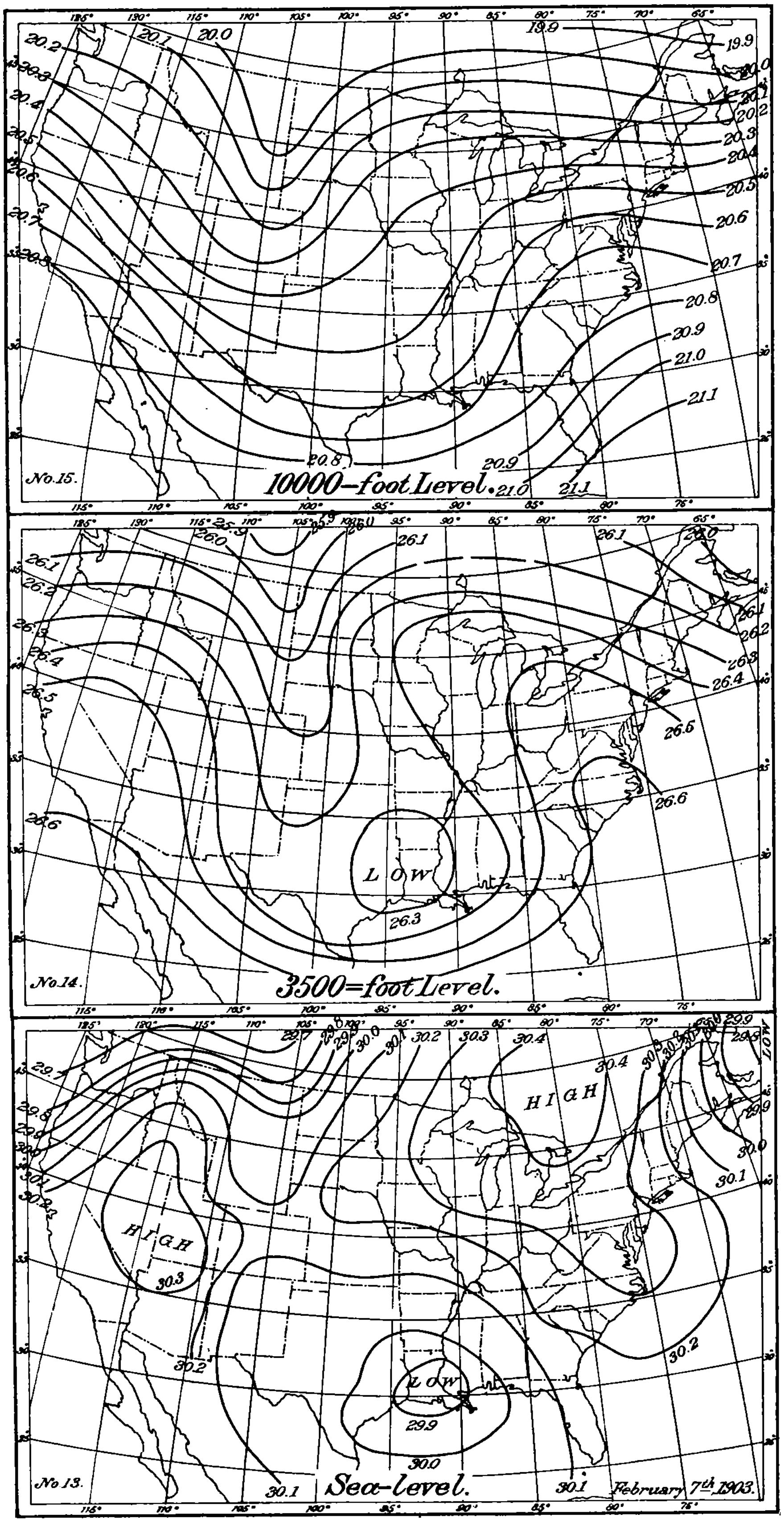
In order to account for the phenomena observed in cyclones and anticyclones, there have been two distinct lines of discussion, (1) the thermodynamic theory and (2) the hydrodynamic theory. The former required a warm central current of rising air to form a vortex. The Espy hypothesis, that the heat necessary to drive the vortex is derived from the latent heat of condensation evolved in changing aqueous vapor into water of precipitation, has been strenuously maintained by many students. There are, however, numerous serious objections which can not be set aside, and these have caused during the past few years a general abandonment of the theory as a true account of the primary cause of cyclones. Ferrel worked out his theory by means of a special type of vortex with closed boundaries, but this does not, unfortunately, in the least satisfy the observations, and it has been rejected as the result of such discrepancy. The equations of motion admit of solution by a different vortex, which more nearly conforms to the requirements of the problem, but no driving force sufficient to sustain a cyclone was discovered before the one suggested by the Weather Bureau research, so that up to recent times the local vortices remained to be fully accounted for on a sound physical basis. The second theory of the local circulation considers it as simply a question in hydrodynamics, where the local thermal force is subordinate to the driving action of the great whirl which gyrates about the pole as a center. In this view the eastward drift simply curls up at places and forms eddies in the great current, and they are borne along by it. This seems to be the general idea adopted by Professor Hildebrandsson in his recent report. There is undoubtedly a certain amount of dynamic action which enters into the construction of cyclones, but there must also be a powerful mechanical force derived from the effort to restore the thermal equilibrium between currents of different temperatures. We shall, therefore, endeavor to trace out these processes more fully than it was possible to do a few years ago and explain a very probable theory of the interaction of the forces that generate and sustain these local storms.

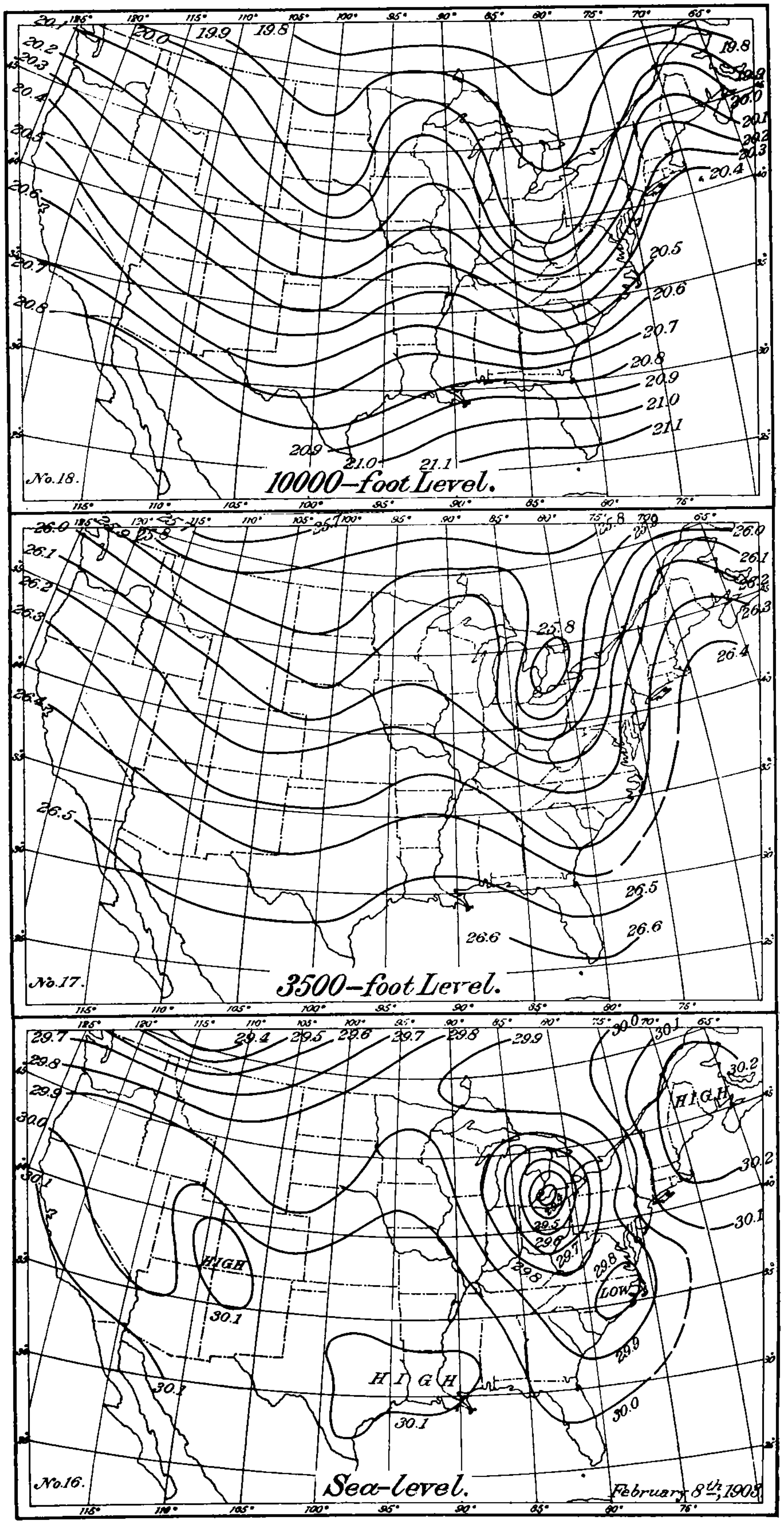
THE ISOBARS AND STREAM LINES ON THE SEA-LEVEL PLANE, THE 3500-FOOT PLANE, AND THE 10,000-FOOT PLANE.

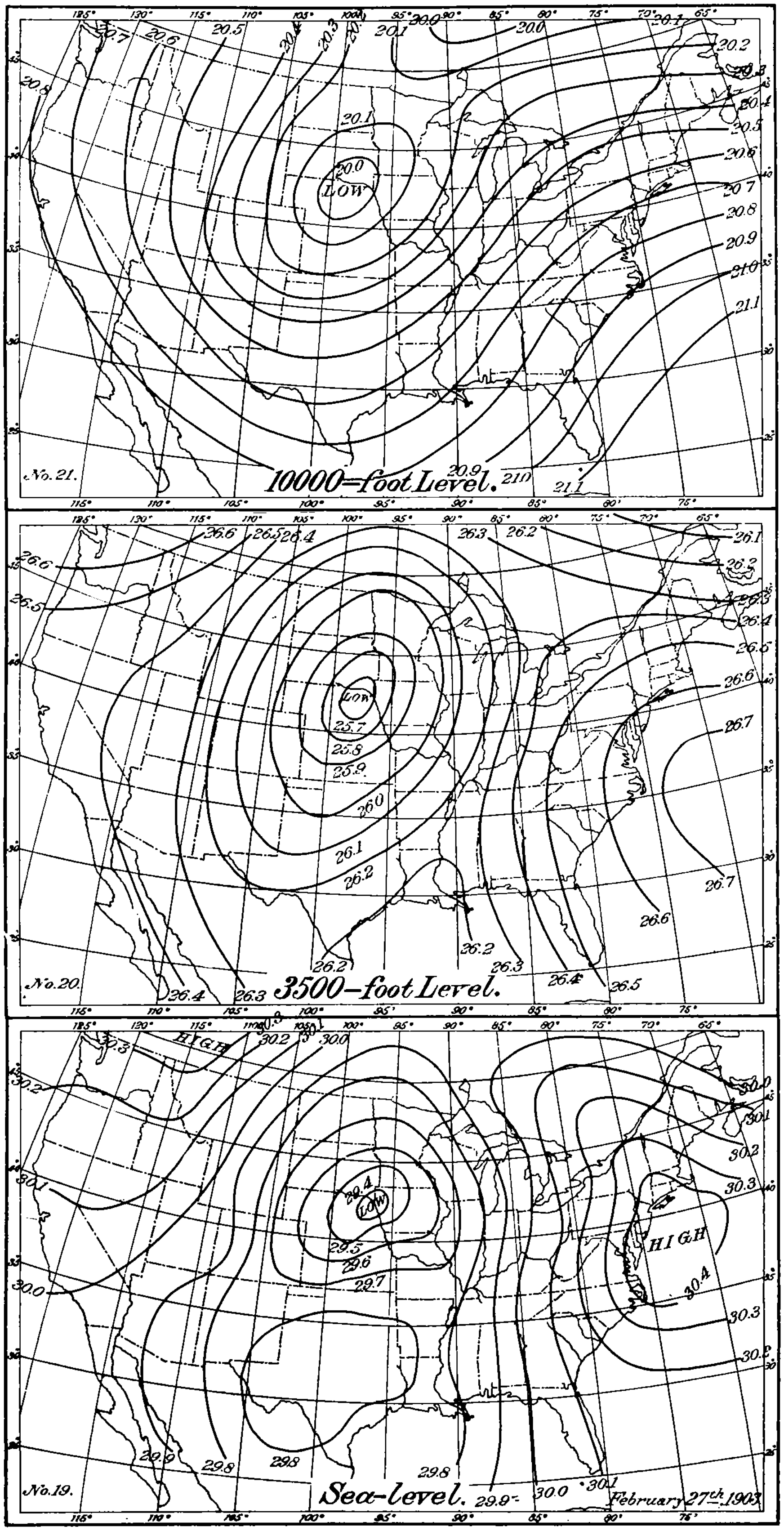
It is first necessary to recall briefly the results derived by the Weather Bureau in its research into this problem. A consideration of the available meteorological observations above the surface of the ground convinced me that it would be necessary to depend upon computations rather than upon direct observations, in order to obtain the daily synoptic pressures and temperatures upon any given reference plane. Observations by balloons, kites, theodolites, or nephoscopes are indispensable in order to secure the necessary data for making the reductions and for checking the results, but it is not possible to make observations on any elevated plane in sufficient numbers to construct a daily map of the weather conditions without adding many laborious corrections. It was, therefore, apparent that suitable methods of computation must be devised for this special purpose in order to reduce the problem to practise. The Weather Bureau now possesses complete barometry tables for the isobars on three planes, and is working out the data for the corresponding isotherms. We have, however, approximate temperature gradients which can be used for the present, in all the preliminary discussions. The thermodynamic formulæ for the α, β, γ, δ stages have been adapted to tables for the computation of B, t, e at different elevations. It was indispensable to substitute these tables for the Hertz diagram, because that is liable to an error as large as 7 millimeters, owing to the neglect of the vapor tension in evaluating the numerical data. Since we require vertical gradients of pressure to within 0.01 millimeter, it is practically impossible to secure that degree of accuracy if the vapor tension is rejected.

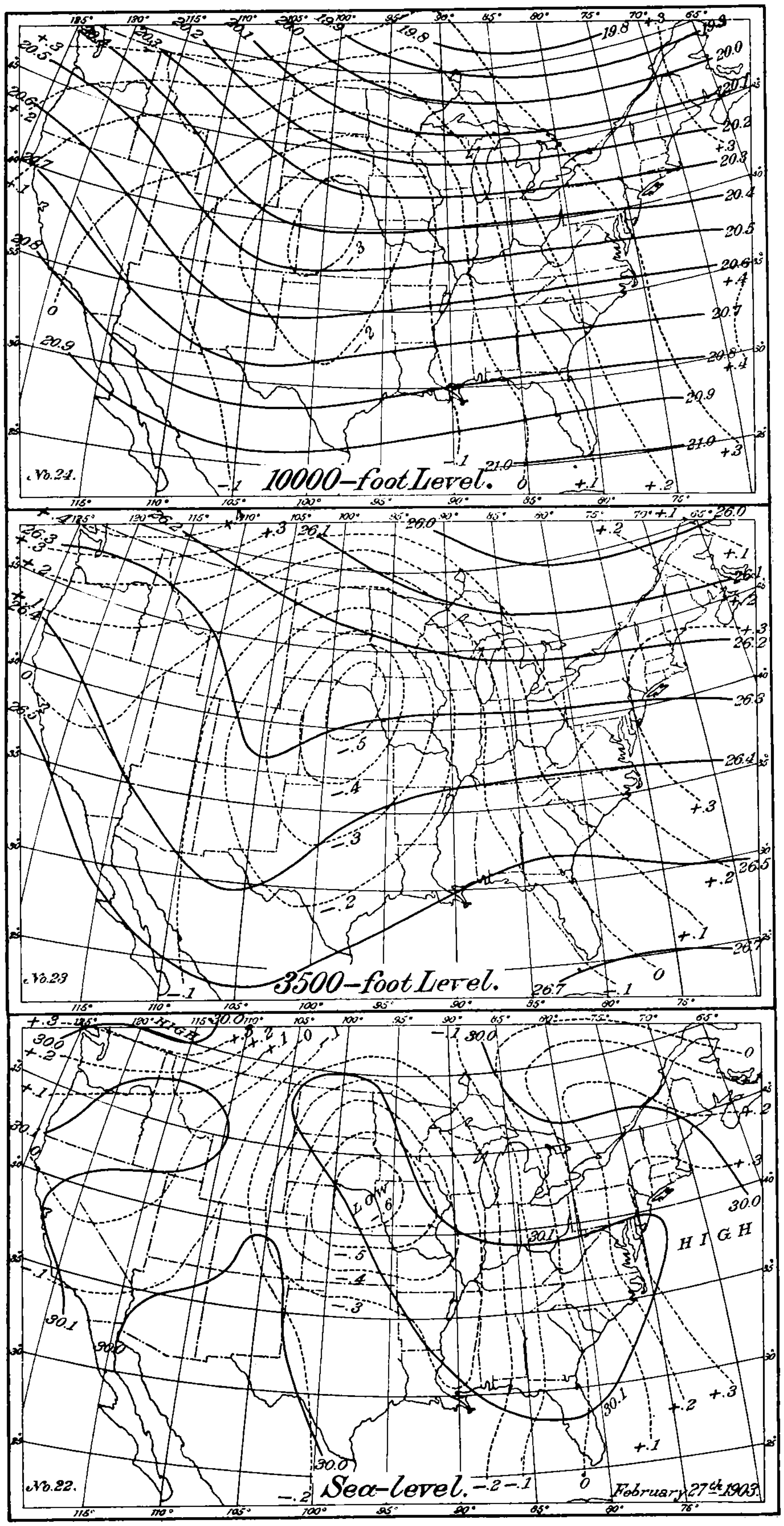
In the MONTHLY WEATHER REVIEW for January, 1903, charts of the isobars, figs. 1 to 6 for January 2, and figs. 7 to 12 for January 7, are given on the three planes; the two components into which they were resolved are also charted, namely, the normal isobars for the month, as given on Charts 28, 30, and 31 of the Barometry Report, and the local disturbing isobars, which are approximately circular in form at the center, the other lines having special curvatures which will be explained. In the present paper there are similar charts, figs. 13 to 15 for February 7, 16 to 18 for February 8, and 19 to 24 for February 27. In order to resolve the observed isobars into the components, the normal isobars of the month were copied on tracing paper; these were superposed upon the computed isobars of the given date, and the diagonals were then drawn to form the second system of components. Attention should be fixed upon one characteristic feature in these charts of isobars, which is readily recognized on nearly every map. To the north or northeast of the closed isobars around the low center, there is a cusp-shaped set of isobars forming a saddle between two isobars of the same name; thus, on fig. 19, the cusps 30.0 between isobars 29.9; on fig. 20, 26.4 forms the cusps of a saddle between 26.3; and on fig. 21, 20.2 forms the cusps to 20.1.

By referring to Maxwell's Electricity and Magnetism, Volume I, Plate III, an analogue to this typical construction in electrostatics is to be found; his Plate I is an analogue to a cyclone in relation to the general circulation around the pole, and Plate II is an analogue to an anticyclone. These figures are constructed by the precepts on page 169, so that the resulting isobar is by analogy $B = B_1 + B_2$, where B_1 refers to the general isobars and B_2 to the local isobars. In the electrostatic analogue the potential is found by the law $V = \frac{e}{r}$, where the successive values 1, 2, 3 are assigned to V, and r is computed from a given value of e. In the case of the isobars, the differences are nearly equal to each other in the general system,


No. 15.
10000-foot Level.
No. 14.
3500=foot Level.
LOW
No. 13.
Sea-level.
HIGH
HIGH
LOW
LOW
February 7th 1903.


No. 18.
10000-foot Level.
No. 17.
3500-foot Level.
No. 16.
Sea-level.
February 8th, 1903.


No. 21.
10000-foot Level.
LOW
No. 20.
3500-foot Level.
LOW
No. 19.
Sea-level.
HIGH
LOW
HIGH
February 27th 1903


No. 24.
10000-foot Level.
No. 23
3500-foot Level.
No. 22.
Sea-level.
HIGH
LOW
H I G H
February 27th 1903.

and in the local system the gradients may be taken, for example, about twice as great. Specifically, on the normal charts the pressure difference is $G = 0.1$ inch for about one and three-fifths degrees in latitude, or 180,000 meters, or 112 miles. A vigorous cyclone is formed by superposing about eight circles, with the gradient $G = 0.1$ inch for four-fifths of a degree, or 56 miles. The irregularities arising from the distortion of either typical system give rise to problems on the conditions of cyclones and anticyclones which are of much interest. In the case of electrostatic force we deal with potentials and lines of force; in that of pressure with stream lines and gradients, since in the frictionless upper strata of the atmosphere the lines of motion are parallel to the isobars unless under special dynamic conditions. Now, on Charts 36 and 39, of the Cloud Report, are shown isobars after Teisserenc de Bort, drawn about the pole at the elevations 1500 and 3000 meters, respectively. This corresponds with the system of large circles in the electrostatic analogue. On Charts 30 and 31, of the Barometry Report, giving the normal pressure for the 3500-foot and the 10,000-foot planes, we have constructed the lines accurately for one special area in the general system of isobars, namely, that covering the United States, and these are similar in form to those from Teisserenc de Bort, though numbered differently in the inches on account of changes in the adopted heights. They are drawn as perfectly as possible and may be trusted to represent the result of eliminating the local cyclonic circulations.

The maps of pressure and temperature given as Charts VIII and IX of the Monthly Weather Reviews for January and February, 1903, agree closely together in their curvature relative to the pole. By comparing with these high level isobars and isotherms the wind directions determined for the upper cloud system, as shown on Charts 20 to 35 of the Cloud Report, it is possible to infer that the stream lines of the general circulation are parallel to the lines of equal pressure and temperature in the higher strata of the atmosphere. The divergences from this system, which occur at any place, are, therefore, not due to the action of the forces of sliding friction such as produce eddies, but to the interplay of dynamic forces of motion derived from other sources. Furthermore, it is simpler to determine the direction of these common lines, the isobars, isotherms, and vectors of motion in the upper atmosphere by computing the isobars and isotherms from the surface data than by the laborious compilation of wind directions and velocities by means of cloud observations, from which the resultants may be deduced. That is to say, we may have daily stream lines on the upper planes by computation from surface data, which are as reliable as those which would be obtained from a long series of cloud observations reduced to annual or monthly means. This is a practical conclusion of much value in meteorology. The isobars on Charts 37, 38, 39, 40 of the Cloud Report, from the data of Teisserenc de Bort, show that there is a greater density of the gradient lines from latitudes 25° to 60°, than nearer the equator or the poles. Therefore the pressure gradient is stronger over the United States than in the tropical or in the polar zones. Such a diminution of the general gradient in lower latitudes is in accord with that theory of the general circulation which drives the currents westward in the lower strata of the Tropics; in the higher latitudes the decrease in gradient indicates a feeble tendency to form a belt of winds flowing westward near the pole. It is a tendency only, because the gradient does not reverse but continues to diminish to the pole, and the motion is everywhere eastward. This is another fact in contradiction to the canal theory, and it also implies that the return circulation of cold air from the poles to the Tropics sets in near the latitudes of 50° to 60° in the descending anticyclonic structure, where the cold streams originate in connection with local areas of high pressure, rather than in the polar zone. The cyclones and anticyclones in middle latitudes are the natural products of the thermal interchange of heat between the "sources" which are in the warm currents and the "sinks" which are in the cold currents. This is not brought about through cooling a northward current in the highest strata of the atmosphere by its radiation of heat into space, or by vertical expansion in the Tropics, as the canal theory requires. The hot and cold masses of air, so far as they are produced by the differences of insolation in the lower layers of the atmosphere, are brought together into physical contact through the low level countercurrents, which are the winds from the south and from the north, respectively. These currents of different temperatures form the natural equivalents to the boiler and the condenser in a thermal engine, and the Carnot cycle is applicable to the analysis of the cyclic processes. The stream lines observed in the motions of the atmosphere as local circulations are built up by the struggle there going on to restore the thermal equilibrium and uniform temperatures. This countercurrent theory is an effective one, in that it brings the abnormal temperatures of the atmosphere into contact through the streams of different temperature, so that they can work mechanically upon one another. The canal theory keeps the currents separated throughout the entire circuit, so that the assumed cooling and heating in the circuit is more like the local heating of a closed current at one portion, while it cools in traveling through the remainder of its course. There is little mechanical efficiency in that process, and it is not useful as a meteorological theory, nor in accordance with the facts of observation.

A certain average excess of heat in the Tropics is required to keep the general cyclone moving at its observed rate of gyration in the upper strata. The thermal equator of such motion moves annually in latitude northward and southward, and this carries with it the entire thermal engine in its annually changing configuration. In the northern winter the thermal equator is far to the south, the contrast between the north polar cold and the tropical heat is much increased, and the general cyclone is relatively efficient; in the northern summer the thermal equator is far to the north, the difference of temperature between the boiler and the condenser of the northern engine is less, so that the circulation is relatively feeble. This oscillation of the heat energy northward and southward, carrying with it the thermal structure toward one pole or the other, just as the astronomical zones of day and night move up and down the earth in latitude, is depicted in the series of diagrams of normal pressure shown in Charts 28 to 31 of the Barometry Report.

The corresponding variations of the temperatures are given on Charts 18, 19, 20, and of the vapor tensions on Charts 23, 24, 25 of the same report. The functions of B, t, e, which are involved in these variations, constitute the basis for a complete solution of the forces that generate and maintain the general circulation in middle latitudes. If we could extend this system of pressure and temperature charts to the pole, and to the equator on the American Continent, and also obtain the vectors of motion, it would afford the required data for the discussion of the dynamics involved in the circulation of the entire atmosphere, and this is the ultimate problem of our meteorology.

The variations of this general circulation from season to season should be extended to include its average changes from year to year, and also the connection of these with that part of the solar energy which is expended as radiation, and is variable in long and short cycles. This will form a science of cosmical meteorology upon which long range forecasting of the seasons can be based. Unless the subject proves to be too complex for human skill to classify, we shall eventually construct a meteorology rivaling other branches of astrophysics in interest and value to mankind.

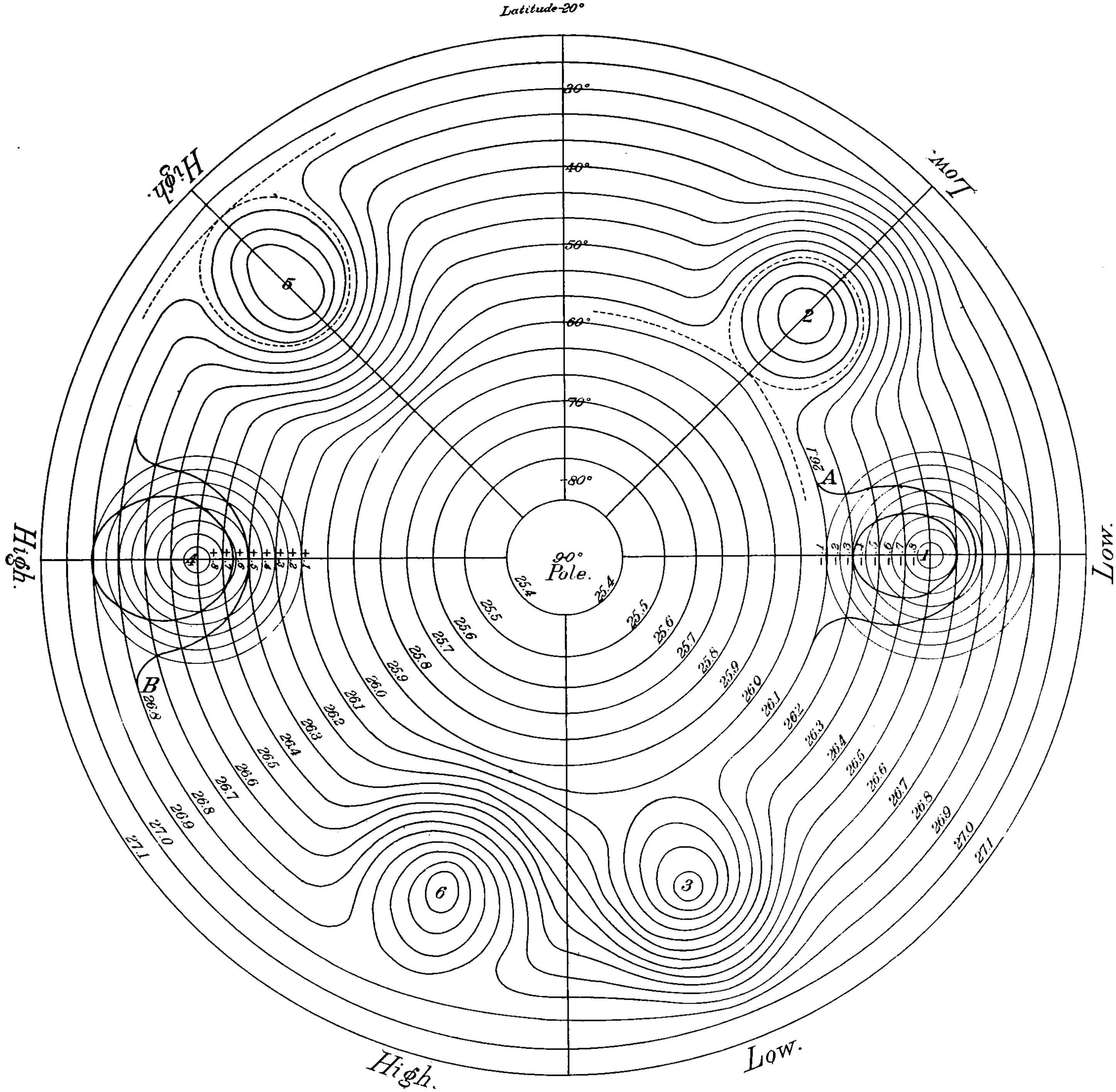


Fig. 25.—The formation of local anticyclones and cyclones in the general circulation about the poles.

THE MECHANISM IN CYCLONES AND ANTICYCLONES.

Turning now from these considerations regarding the general circulation to the mechanism of local circulations, we will further illustrate the separation of the local components from the general normal isobars by the six diagrams of fig. 25, the formation of local anticyclones and cyclones in the general circulation about the pole. We draw 18 concentric circles about a pole as a center, where the common difference is 5 millimeters, except in the polar zone where the difference is greater. The outer circle extends to latitude 23°, that is to Havana, so that these circles cover the latitudes in which the cyclones are produced in northern latitudes. Diagrams 1, 2, 3, show the method of constructing a low pressure area, and 4, 5, 6, that for a high pressure area; diagrams 1 and 4 give examples of the drawing of a few individual resultant curves; 2 and 5 are complete for isolated low and high areas; 3 and 6 exhibit the connection between a high and a low area, and this diagram is comparable with the isobars found on the charts of reduced pressures, as figs. 13, 14, 15, 16, 17, 18, of this paper. In making these specimen diagrams a system of local circles is superposed upon the general circles, but the common difference between them is taken half as much linearly, that is the gradient is twice as steep. On the general circles 5 millimeters is equivalent to 0.10 inch of pressure, on the small circles 2.5 millimeters is equivalent to 0.10 inch of pressure. These relative dimensions serve approximately to illustrate a strong winter cyclone, but they should be modified according to the observed conditions of the individual cyclone. When the monthly normal isobars are subtracted from the observed map of a given day, we have at once the small circular system, together with its variations from the normal type according to the prevailing circumstances. Looking at diagram 1, of fig. 25, we see that in passing from the pole outward each circle is + 0.10, one-tenth inch higher, beginning for example with 25.4 and extending to 27.1. The small circles are numbered — .1, — .2, — 3, . . . for the low area, and + .1, + .2, + .3, ... for the high area. At the point *A* we have 26.1 on the large circle; on the next circle it becomes, 26.2 — 0.1 = 26.1, by uniting the two gradients; on the next it is, 26.3 — 0.2 = 26.1. In this way, drawing the diagonal lines, we pass around a U-shaped curve having a certain concavity. Other curves are formed outside and inside of it, a few of the inner curves making closed ovals, eccentric to the center. The dotted curve on diagram 2 shows where the cusp-shaped curves unite over the saddle of higher pressure. The diagrams 4 and 5 are drawn in a similar way, by using the plus system of circles. At *B* we have 26.7 + 0.1 = 26.8; 26.6 + 0.2 = 26.8; 26.5 + 0.3 = 26.8 . . . Similarly the other lines are drawn. Finally, in diagrams 3 and 6 the two systems are united, so that the lines flow from one to the other continuously. It should be noted that in fixing the centers of the two systems of component coaxial circles, that for diagram 3 was placed on the isobar 26.5, and that for diagram 6 on the isobar 26.4. That is to say, the center of the anticyclone must be nearer the pole than that of the cyclone, in order to make the isobars continuous, otherwise some of the ends of these systems of high and low areas are left unconnected and without natural continuity.

A comparison of these typical isobars with those constructed from the daily observations, see figs. 1 to 24, proves conclusively that they are substantially of the same type. We find the cusp formation on each with the opening of the U-shaped figure toward the pole in the cyclone, but toward the equator in the anticyclone. The closed curves of the cyclone are more nearly elliptical than those of the anticyclone, as is commonly the case on the weather maps. The flow of air from the northern quadrants of the anticyclone toward the southern quadrants of the cyclone is necessary to the structure.

COMPARISON WITH OTHER OBSERVED CONFIGURATIONS.

In order to recall the results of the research which are included in the Cloud Report, the following drawings are introduced. Fig. 26 shows the vectors of motion and their components as observed in anticyclones and cyclones at the 1000 meter (3280-foot) level, and the 3000 meter (9843-foot) level, so that these are comparable with the isobars computed on the 3500-foot and the 10,000-foot planes. The direction of the original vectors is evidently parallel to the isobars, the long vectors which indicate greater velocity are to the north of the anticyclone where the isobars are closer, and then to the south of the cyclone where the closeness of the pressure lines is a maximum. Comparing the anticyclonic and cyclonic components with the resolved local isobars on the charts of observed pressures, figs, 1 to 24, the opening of the stream lines marked *A* on the cyclone corresponds with the opening in the U-shaped clone, similar conditions are found to the south of the anticy- cusps. Furthermore, in fig. 27, I, II, III, three charts are reproduced from the Cloud Report; Chart 23, the mean winter Lake region low; Chart 29, the mean west Gulf low, each for the lower clouds; and Chart 35, the mean summer hurricane low for the upper clouds. The stream lines flow uninterruptedly to the center on spiral or disturbed spiral curves, one stream from the northwest and another from the south, and to the north of the center the same U-shaped cusp formation is described by the vectors of motion as are found on the charts of isobars. It is remarkable that in the case of the hurricane this formation is found in the cirrus levels, just such as in ordinary cyclones is produced in the cumulus levels, showing that this fundamental typical construction penetrates to the height of 5 or

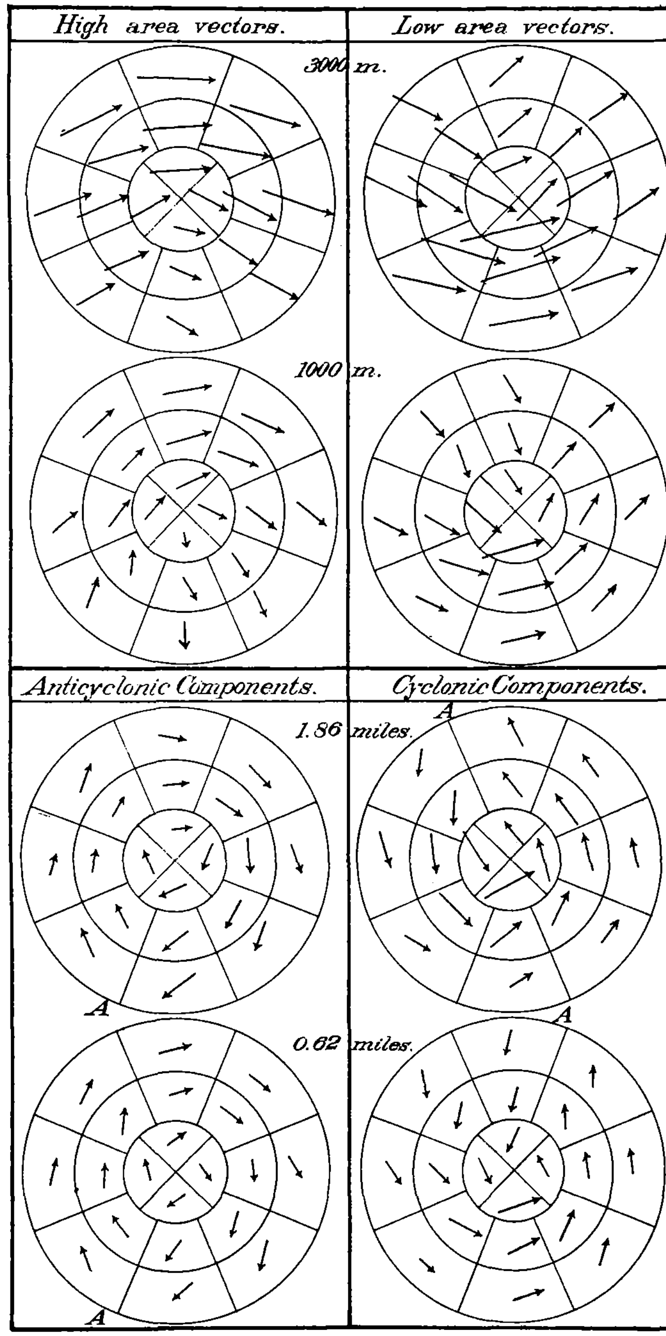
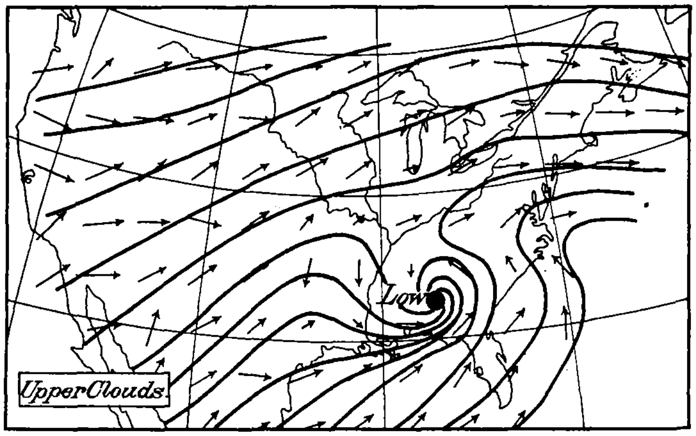


FIG. 26.—The vectors of motion and their components in anticyclones and cyclones at the 1000-mile and 3000-mile levels.

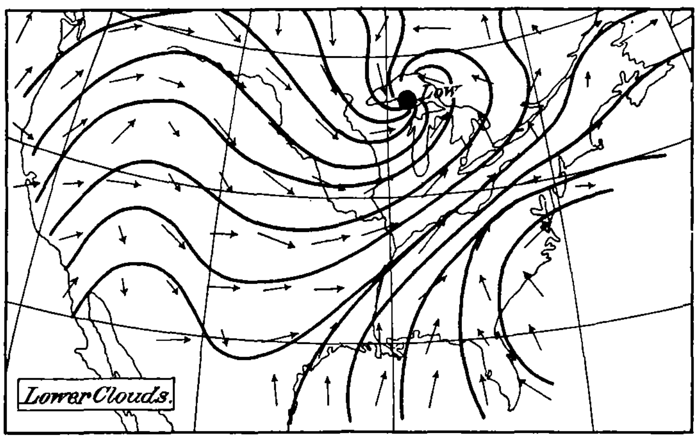
6 miles, when the forces of motion producing it are sufficiently intense. The relative penetrating power of the cyclonic action is a very important feature, which is brought out by these isobars and stream lines in the higher levels.

Furthermore, consider the component local isobars in dotted lines on figs. 4, 5, 6, for January 2; 10, 11, 12, for January 7; 22, 23, 24, for February 27. On January 2 it is evident that the principal feeder is a current of warm air flowing over the South Atlantic States, which curls into the closed isobars from the northward; here the cusp formation is somewhat obscure, and this usually happens while the center is so far to the south. On January 7 the main stream feeds into the vortex from the northwest, and on the western and southern sides, where the isobars are dense, the stream curls into the center. On February 27 there is a strong stream from the southeast and another from the northwest, both of which curl strongly into the central vortex.

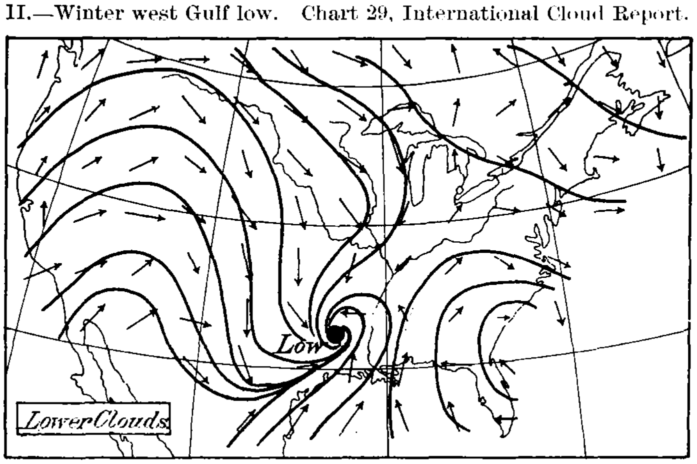
It should be particularly noted that the stream curls into the central vortex at all levels from the ground upward, crossing the closed isobars at some angle, but running parallel to the open isobars, thus confirming the results of the Cloud Report.



III.—Summer hurricane low. Chart 35, International Cloud Report.



II.—Winter west Gulf low. Chart 29, International Cloud Report.



I.—Winter Lake region low. Chart 23, International Cloud Report.

FIG. 27.—The stream lines in cyclones and the cirrus levels in hurricanes.

It should be observed, also, that the U-shaped opening in the northern cyclones is swung around to the northeastward, thus distorting the lines from their primary position of symmetry, which is toward the pole. This is due to the fact that the cyclone has vertical and gyratory components which penetrate from lower to higher levels, and therefore into the upper layers, drifting more rapidly eastward than the lower. Such distortion is accompanied by an interchange of the inertia of motion, and this is the part of the thermal machine of the atmospheric circulation which acts as a brake upon the swiftly flowing eastward drift. This is the means by which the eastward velocities are slowed down from the excessive motions required, in the general theory by the law of the preservation of vortex areas, into the moderate motions actually observed. Since this penetrating power may extend to the cirrus levels, the total energy of retardation is evidently very great, and therefore this portion of the problem of the general circulation should be developed on the lines already outlined in my papers, rather than on those followed by Professor Ferrel. Furthermore, we remark that my construction is not in accord with the theory of the German vortex, as also explained in that report. This vortex requires a local center of heat and a vertical current, with zero velocity at the center and maximum velocity at a circle on the edge of the closed curves, from which locus it gradually falls away to zero again at a considerable distance. In nature we have, on the other hand, individual stream lines of different temperatures curling into a common center, with velocity increasing up to the very center, as indicated on Chart 69 of the Cloud Report. The German vortex is much nearer the natural type than the Ferrel vortex, but there are features in it which are not compatible with the observations themselves. The disturbance of the eastward drift by the penetration of a cyclonic vortex into the upper strata is further illustrated by the scheme of fig. 28, where the successive levels are

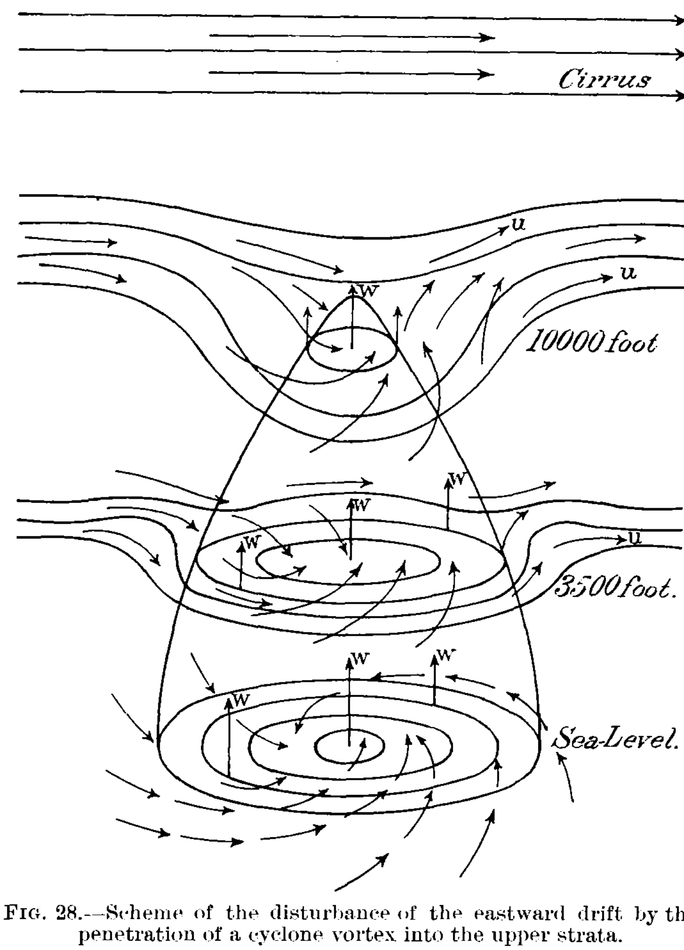


FIG. 28.—Scheme of the disturbance of the eastward drift by the penetration of a cyclone vortex into the upper strata.

shown with the isobars bending away from their normal eastward direction, first into U-shaped curves about the axis, then to cusps and closed curves, and finally to simple closed curves at the surface. These closed curves always imply a vortex with its vertical component governed by the usual vortex laws. The boundary of the true vortex action diminishes in size, and loses itself in the upper strata as a simple sinuous deflection. The vortex throws up a vertical component all over its area in proportion to the gyratory velocity, and in the center this forms a rising current, continuous and undisturbed, till high levels are attained. On the edges, however, the vertical component is stripped off by the action of the eastward drift, which also acts more powerfully in proportion to the elevation. This depletion of the surface of the vortex in proportion to the height is the mechanical mode that controls the escape of the upward current, which loses itself to the eastward by merging in the general circulation, whence it passes through other anticyclones and cyclones in succession. The radial horizontal component is inward toward the center in all levels of the cyclone, as was indicated in my Cloud Report. Thus, the entire complex of the circulation has dynamic components, and the energy thus expended must be referred back finally to the source of heat in the Tropics, where the absorption of radiant energy from the sun goes on vigorously at the surface of the earth. The great general cyclone is perpetuated by the vertical uplift of the strata, due to the residue of the tropical heat which does not leak out toward the poles in horizontal warm currents of air near the surface, and its motion is in general nearly independent of the counterflow of these lower currents, except for the distortion due to the penetration just described. We have therefore established the existence in the cyclone of the interaction of three practically independent currents of air, (1) the great overflowing eastward drift, (2) the underflowing cold current from the northwest, and (3) the underflowing warm stream from the south.

THE INTERACTION OF THE THREE THERMAL CURRENTS.

It is necessary yet further to consider the thermal action of these currents which have very different temperatures. For it is evident that the formation of local closed isobars with vortex action and vertical currents, while accompanied by dynamic forces must yet depend upon a powerful and persistent thermal source. We have elsewhere shown that this energy is not to any great extent the latent heat of condensation of aqueous vapor, this being a secondary product; nor is the effect purely dynamic as the eddy theory implies. Where, then, shall we find a true efficient source of heat that is competent to account for all the conditions observed in the circulation phenomena of the atmosphere. It seems to me that this is to be attributed to the *thermal action due to the overflow of layers of cold air upon masses of warm air.* Abnormal stratification of air currents, where the relatively cold is above the warm, necessarily involves an upward current having an energy proportional to the difference of temperature. It is not necessary to say more about the truth of the view that this stratification exists, because such an overflow is really one of the most common conditions to be observed in meteorology. If a warm current leaves the latitudes of the high pressure belt, 35° more or less, and runs northward, it begins to underflow the eastward drift. If a cold area slides down from the northwest into warm latitudes, its upper portions are drifted forward over the warm lower strata. If two currents counterflow together the cold western masses are drifted forward upon the warmer at moderate levels, also warm masses are carried eastward over the next anticyclonic area. The instant the normal thermal equilibrium of the atmosphere is disturbed by such stratifications, thermal energy is present for the formation of dynamic vortices. Thus a hurricane begins in the late summer when the sun retreating southward brings the first layers of cool air to overspread the Tropics in a sheet. The warm surface air then begins to flow under this and penetrates it in a vortex, and this continues to operate as long as the flow of current sheets of two temperatures from the different sources continues. The track of a hurricane can thus traverse thousands of miles, because the cold overflow sheet covers the temperate zone, and the warm underflow current is directed in streams depending upon the general circulation of the lower air about the permanent anticyclonic centers of action. A specific example will make these remarks more definite.

In the Cloud Report we took great pains to construct the abnormal gradients of pressure, temperature, and vapor tension, such as are observed when the cumulus clouds are in the process of formation. These gradients are to be found in Tables 147, I to VII, for the metric system, and in Tables 153, I to VII, for the English system. By entering these tables with the prescribed arguments we can find the gradients which are prevailing at a given level in a cyclonic circulation. These tables are constructed primarily in reference to the 3500-foot plane, but they can be extended to other levels by the adjoining precepts, if some judgment is exercised. Furthermore, it was essential to establish the normal conditions which prevail in the atmosphere at two higher planes, so that the difference between the normal gradients, which may be readily computed from the mean monthly values as given in the Barometry Report, and the abnormal gradients, which pertain to the different subareas of cyclones and anticyclones, may be obtained. This was one of the purposes that was kept in mind in constructing the Barometry Report, and the data for such normal gradients are given in Table 48. By subtracting the numerical values for B, t, e, on the different planes, and dividing by the difference in elevation, these normal gradients are found. By using the surface data in connection with the three selected planes, we obtain several systems of gradients which can thus be computed for mutual comparison. As to the abnormal gradients of temperature, for example, we may take from Table 153, II, of the Cloud Report, the values for the different subareas in a cyclone, the table being quoted only in part.

TABLE 1.—*Pressure and temperature gradients in English measures.*

FALL OF PRESSURE IN INCHES PER 100 FEET.

$\frac{e}{B}$ / t ° F.	.0100	.0120	.0140	.0160	.0180	.0200	.0220	.0240
90	......	......	0.095	0.095	0.095	0.096	0.096	0.097
80	......	0.096	.097	.097	.097	.097	.098	.099
70	0.098	.099	.100	.100	.101	.102	.102	.103
60	.102	.103	.104	.104	.105	.106	.107	.108
50	.105	.106	.107	.107	.108	.109	.110	
40	.107	.108	.109	.109	.110	.111		
30	.109	.110	.111	.111	.112			
20	.113	.114	.115	.115				
10	.117	.118						
0	.120							

FALL OF TEMPERATURE IN DEGREES PER 100 FEET.

$\frac{e}{B}$ / t ° F.	.0100	.0120	.0140	.0160	.0180	.0200	.0220	.0240
90	......	......	......	......	0.88	0.82	0.74	0.240
80	......	0.85	0.82	0.74	.65	.58	.52	.47
70	0.79	.68	.59	.51	.43	.37	.34	.31
60	.59	.48	.40	.33	.30	.28	.27	
50	.41	.33	.25	.20				
40	.26							

From Table 153, International Cloud Report.

In the eastern subareas we have high temperatures and high vapor tensions (t_1, e_1) so that the temperature gradients are large; in the western areas the temperatures and also the vapor tensions are lower (t_2, e_2). Then (t_1, e_1) will give larger values of $G.\ t_1$ than (t_2, e_2) will give for $G.\ t_2$. If the $G.\ t_1$ exceeds the normal gradient of the season, we have the mechanical cause for a vertical current. This principle can be applied throughout the cyclonic field with unfailing results of the right kind. In general it may be stated that the normal temperature gradients are about three-fifths the adiabatic rate, and this occurs when the strata are in atmospheric equilibrium and no currents are distinctly rising or falling. In cyclones and anticyclones, where the vertical currents are pronounced, the temperature gradients are about the same as the adiabatic rate. This remarkable theorem regarding gradients is very significant in the physical thermodynamics of the atmosphere. Hence, we conclude that air is rising to the east, but falling to the west of the center of the cyclone. It seems almost a paradox that in the warm current of air the air should be rising to a region where the pressure is higher than it was before the movement began. But rising air always increases the pressure in the stratum to which it is moving, and this hardly needs to be reaffirmed. The overflowing cold air in the strato-cumulus level, therefore, in itself generates the power which raises the warm air underneath it by the usual thermodynamic laws. Hence, if a relatively cold layer is thrust into a column of air otherwise normally disposed, the warm lower layers will rise to meet the cold stratum, and the higher strata which are also relatively warm will fall toward it. Relatively warm air flows to the place of relatively cold air. If the surface layers are cooled by radiation in anticyclones the air of the upper strata will settle down upon them by this law, namely, that relatively warm air seeks relatively cold air. The currents of transfer thus set up have an adiabatic system of gradients; on the other hand, the normal layers of the atmosphere do not dispose themselves into adiabatic strata, as was proved in my Cloud Report. Some specific examples of the operation of these processes will now be mentioned.

EXAMPLES OF THE INTERACTION OF ABNORMALLY COLD AND WARM STRATA.

A survey of the conditions prevailing at the time of the waterspout photographed on August 19, 1896, off Cottage City, in Vineyard Sound, Mass., leads me to the results contained in Table 2, extracted from a report now in preparation on this important phenomenon. It contains for the α, β, γ, δ stages the heights on the photograph in millimeters and inches, the actual height in meters and feet, and the pressure, temperature, and vapor tension at the beginning and end of each stage. Thence the gradients are found per 100 meters, or per 100 feet, viz: (1) (G_o) Observed, according to the actual observations, (2) (G_c) Cloud, according to the Cloud Report Tables 147 and 153, and (3) (G_b) Barometry, the normal gradient prevailing in the air for that month as deduced from Table 48 of the Barometry Report. This waterspout was formed under remarkable conditions. The pressure was a little high, 30.05 inches; the temperature was exactly normal for the month of August, 67.5° F., and the vapor tension was low, corresponding to a relative humidity of 64 per cent. This gives the ratio $\frac{e}{B} = 0.0143$ from which the gradients (G_c), cloud, were obtained. Comparing (G_o), (G_c), and (G_b) we note that (G_b) is less than (G_o) and (G_c) in both the pressure and the temperature, but greater in the vapor tension for both the α and β stages. This waterspout was formed in a congested region on the southeast edge of a great area of high pressure, which was pushing over the New England coast line at that time, and there was no cyclonic action of any kind. There was then generated a rapid formation of cumulo-nimbus clouds, with rainfall at the front, waterspouts in the middle, and thunderstorms with hail following, all in the course of a couple of hours. I conceive that this entire set of phenomena was due to the drifting forward (in the strato-cumulus level) of the relatively cold air of the anticyclone as a sheet overspreading the quiet layers of relatively warm air resting on the ocean. The normal temperature at the ocean level is 67.7° F. for August, and 60.4° at the 3500-foot level. But by computation the temperature was 48.7° at that level, giving an abnormal fall of 11.7° F., due to the overflowing of the cold stratum from the advancing anticyclone. This great fall in temperature was not caused by any change in the surface conditions, which remained normal till the thunderstorm following the rain and waterspouts brought the cold air to the surface and caused the temperature to fall at the ocean also. The cold upper stratum evidently preceded the surface cold air by several hours, and this is typical of the conditions frequently prevailing in similar local congested circulations of the lower strata, where abnormal stratification and so-called inversion of temperature is observed. This ab-

TABLE 2.—*Summary of the data for the Cottage City waterspout, August 19, 1896.*

Stages.	Metric system.					English system.					
	H. photo.	Height.	B.	t.	e.	H. photo.	Height.	B.	t.	e.	
	Mm.	*Meters.*	*Mm.*	*°C.*	*Mm.*	*Inches.*	*Feet.*	*Inches.*	*°F.*	*Inch.*	
	176.4	4,942	414.5	—12.0	1.64	6.95	16,214	16.32	10.4	0.065	
δ-stage....	73.6	2,062	—6.04 —6.50	— 0.582 — 0.550	—0.142 —0.140	2.90	6,765	—0.072 —0.078	—0.319 —0.302	—0.00170 —0.00168	(G_o) Observed. (G_c) Cloud.
	102.8	2,880	539.0	0	4.57	4.05	9,449	21.22	32.0	0.180	
γ-stage....	2.6	74	—6.76	....	....	0.10	243	—0.082	....	....	
	100.2	2,806	544.0	0	4.57	3.95	9,206	21.42	32.0	0.180	
β-stage....	61.7	1,728	—7.40 —7.60 —7.11	— 0.538 — 0.540 — 0.376	—0.240 —0.260 —0.364	2.43	5,669	—0.089 —0.091 —0.085	—0.294 —0.294 —0.207	—0.00288 —0.00312 —0.00437	(G_o) Observed. (G_c) Cloud. (G_b) Barometry.
	38.5	1,078	672.0	9.3	8.72	1.52	3,537	26.46	48.7	0.343	
α-stage....	38.5	1,078	—8.46 —8.40 —8.24	— 0.963 — 0.950 — 0.375	—0.204 —0.192 —0.296	1.52	3,537	—0.101 —0.101 —0.098	—0.531 —0.522 —0.206	—0.00246 —0.00230 —0.00355	(G_o) Observed. (G_c) Cloud. (G_b) Barometry.
Sea level..	0	0	763.27	19.72	10.92	0	0	30.05	67.5	0.430	

normal stratification of cold over warm layers caused the thermal difference necessary to enable the hydrostatic pressure of the neighboring region to cause a vertical current. In this rising air the temperature and pressure gradients changed from the normal rates prevailing previous to the sudden change into adiabatic rates, which seem to have been fully reached in the temperature. There are numerous physical functions useful in meteorology involved in these data, and it will be valuable to compute the B, t, e in the higher strata for as many instances of the kind as is practicable.

Some idea of the energy available to produce a vertical current can be gained from the following consideration: The normal temperature gradient in the α-stage is -0.206 per 100 feet, the observed gradient is -0.531, and this is a gain of -0.325. The normal pressure gradient is -0.098 per 100 feet, the observed gradient is -0.101, and the gain is -0.003 per 100 feet, or 0.106 inch in the α-stage. That would be equivalent to the enormous gradient of -13.5 inches in a degree, 111,111 meters, along the surface of the earth, which is 100 times as great as that observed for the usual horizontal gradients. In the β-stage the temperature normal gradient is -0.207, the observed is -0.294, the increase -0.087 per 100 feet. Comparing this with -0.325, the increase in the α-stage, we conclude that the efficient buoyancy gradient is four times greater in the α-stage than in the β-stage. This is contrary to what should be expected if the buoyancy is chiefly due to the condensation of aqueous vapor to water in the cloud or β-stage, but it is in accord with the theory of stratification proposed in this paper.

We have other examples of the effect of an overflow of a cold stratum upon the warm air of lower levels in the numerous cases where anticyclonic areas advance into the central valleys from the northwest without a cyclonic development in front of them. There is produced in such conditions a wide band of rainfall on the map, stretching from the Lake region to the Gulf of Mexico, where no dynamic action is operating which can raise the air mechanically. The cold, overflowing sheet will, however, cause an increase in the temperature gradient, and this is accompanied by rising air and precipitation over immense areas of country. In certain cases the anticyclonic area will advance to the Atlantic coast before causing such ascending currents, and then a powerful small cyclone sometimes develops suddenly near the coast of New Jersey or Virginia, and as this advances to New England it produces hurricane winds. When two currents of different temperatures flow together in the Mississippi Valley the overflow of the cold layers from the northwest upon the warm layers from the south produces a congested condition, accompanied by thunderstorms, tornadoes, and general violent local circulations in the southeastern quadrants of the cyclone. On the other hand, the wide range in temperature required to cause such rapid vertical circulations may also be produced by simply overheating the surface layers relatively to the upper strata. This is the case in summer, when in anticyclonic areas the solar radiation passes through all the upper layers to the surface without heating them sensibly. Then the earth's radiation, in its turn, does have the power to overheat the lower strata, and this causes an increased temperature gradient relatively to the cumulus levels, which is the atmospheric condition for numerous summer thunderstorms and desert sand squalls. In the winter the areas of low pressure over the northern portions of the Atlantic and Pacific oceans are due to the relatively high temperature of the ocean waters and adjacent air layers. During the months in which the lower layers are too warm in comparison with the adjacent continental areas and with the strata above them, the well-known permanent cyclones prevail. The reverse case occurs in summer over the ocean belts at the boundary of the tropical and the temperate zones, where the water holds the surface strata at temperatures lower than is required for equilibrium, and so causes a settling down of the upper air. This is, of course, an effect which increases the usual dynamic action produced by the general circulation in this high pressure belt.

In the autumn the cold layers advance from the northern zones into the Tropics, first in the higher strata which overspread the warm and moist air of the doldrums. This causes an increase of the vertical temperature gradient, and a hurricane or large columnar vortex is formed, through whose structure the warm air pours upward to great heights, and enables this configuration in some cases to perpetuate itself by such convection for many days. It is the wide spread cold sheet of the upper strata which is the persistent source of energy in a hurricane, and also in a cyclone. The advancing movement of the center is due to the fact that the warm air, which lies to the eastward, promptly rises to meet the overflowing cold sheet, the two mutually sustaining each other's action. The downflow of the cold air on the western side is simultaneous with the upflow on the eastern side, but the deficiency of pressure on one side and the excess of it on the other by its continuous operation causes the entire structure to advance. In addition to this, the drift of the upper strata, eastward in the temperate zone and westward in the Tropics, carries along the cyclone, which adheres to them by the interactions that have been described.

GENERAL RESULTS STATED.

The results of this research may be summed up briefly as follows: (1) The cyclone is not formed from the energy of the latent heat of condensation, however much this may strengthen its intensity; it is not an eddy in the eastward drift; but it is caused by the counterflow and overflow of currents of different temperatures. Ferrel's canal theory of the general circulation is not sustained by the observations, nor is his theory of local cyclones and anticyclones tenable. There are difficulties with regard to the German vortex theory, but this is nearer the truth than the Ferrel vortex. The structure in nature is actually more complex than has been admitted in these theoretical discussions, but it doubtless can be worked out successfully along the lines herein indicated. (2) Regarding the relation of the upper level isobars to practical forecasting, it is noted as the result of the examination of the charts of December, 1902, January and February, 1903, that (*a*) the direction of the advance of the center of the low pressure is controlled by the upper strata, and its track for the following twenty-four hours is usually indicated by the position of the 10,000-foot level isobars; (*b*) The velocity of the daily motion is also dependent upon and is shown by the density of these high level isobars; (*c*) the penetrating power of the cyclone is safely inferred from an inspection of the three maps of isobars of the same date; (*d*) there is decided evidence that areas of precipitation occur where the 3500-foot isobars and the 10,000-foot isobars cross each other at an angle in the neighborhood of 90°; (*e*) there have been several cases in which the formation of a new cyclone has been first distinctly shown on the upper system of isobars before penetrating to the surface or making itself evident at the sea level. (3) It is expected that by completing our discussion of the temperature gradients between the surface and the higher levels we shall be able to secure daily isotherms as well as daily isobars on the upper planes, and this will tend to strengthen any further examination of these important problems. A suitable report will be prepared in which the data now coming into our possession will be subjected to a mathematical analysis and discussion.